Semiconductor nanostructures grown in production MOVPE reactors

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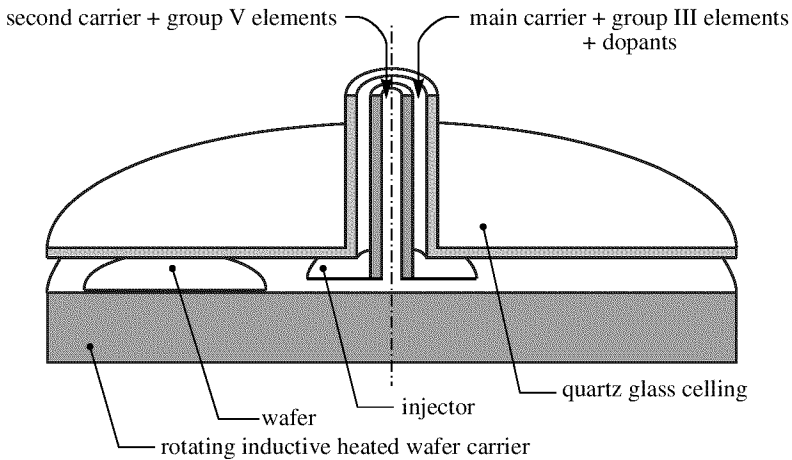AIXTRON AG, Kackertstr. 15-17, D-52072 Aachen, Germany

Abstract.   Since the invention of the Planetary Reactors® a reliable tool for mass production of various III–V compounds and nanostructures based on MOCVD growth is existing. These reactors have proven to grow extremely uniform films together with a highly efficient utilization of the precursors. Their main features are: an inductive heating system with extremely low thermal mass for precise and fast heating, high flexibility in the reactor size ($15 \times 2''$, $35 \times 2''$ to $9 \times 4''$ wafer load) and the option to use a fully automated cassette-to-cassette wafer loading system. The benefits of this design are very short cycle times, extreme run-to-run stability and even further reduced cost of ownership. Uniformity of thickness, luminescence intensity and composition of the most important III–V compounds such as GaInP, GaInAsP and AlGaInP as well as GaN based materials are shown.

Introduction

Physics and technology of semiconducting materials and structures, in particular GaAs-, InP- and GaN-based ones, have developed tremendously in the last 30 years, triggering development and realization of optoelectronic devices. Such devices like lasers, light emitting diodes, modulators, detectors, photovoltaic solar cells, passive elements and electronic devices using the concept of nanostructures present a driving force of enormous economic growth [1]. Most of them are enabling devices, making systems possible that would not exist or function without that particular device. The present value of an "optoelectronic system" is typically a factor 50–200 larger than the value of the mere device. Typical examples of such systems are compact disc players, laser printers and optical interconnects for the consumer, office, computer and telecommunication markets, optical storage and archive systems. Conservative growth predictions for the opto-electronic component market are 15–25% per year, much higher than the average economic growth [2]. In this paper the focus will be on the MOCVD growth technology to realize compound semiconductor based structures rather than on the physical properties of the ultimate electronic nanostructures and quantum dots.

1   The Planetary Reactor® for the MOVPE growth of nanostructures based on III–V compounds

The requirements for a production machine are high throughput, high efficiency and a good uniformity of composition, layer thickness and doping. These requirements are met by AIXTRON Planetary Reactors® due to their unique design which offers real multiwafer capability at a high degree of flexibility. Depending on the chosen setup, up to $95 \times 2''$ wafers can be grown simultaneously in one run. Recently, a new fully automated $35 \times 2''$ or $5 \times 6''$ type has been introduced. The main carrier gas (N_2 and H_2) and the standard group III elements (TMGa, TMAl, TMIn) and dopants (DEZn, SiH_4) were injected in the center of the susceptor with a rotational symmetry. The second carrier gas and the standard group V elements (AsH_3, PH_3, NH_3) were also injected in the center but separated from

second carrier + group V elements ⌐   ⌐ main carrier + group III elements
                                                        + dopants

quartz glass celling

injector

wafer

rotating inductive heated wafer carrier

**Fig. 1.** Planetary Reactor® principle.

the group III elements. This special design of the inlet geometry avoids pre-reactions and allows a very good run-to-run reproducibility and an excellent uniformity. To achieve the good uniformity a precise temperature management of the reactor is necessary. There are several hardware options available to optimize the temperature profile in the reactor for each customer requirement. Absolute growth temperature, gas flow distribution, rotation speed of the main plate and the gas foil rotation of each wafer as well as the gas phase composition are the common parameters which need to be controlled to optimize the layer properties [3]. Details of the reactor performance were investigated by simulation [4].

   In this study we discuss results obtained in various types of Planetary Reactors® used for the growth of InP, GaAs and GaN based materials. Standard growth parameters used in this study are low total gas flows between 20 and 30 l/min (depending on the reactor size) and a total pressure around 100 mbar. Typical growth temperatures used were between 675°C and 750°C for GaAs. All epitaxial growth of GaN based material was carried out using an AIXTRON multiwafer planetary MOCVD system which has a $6 \times 2''$ capacity. Two inch c-plane sapphire wafers were utilized for all growth and the system was equipped with standard Group III precursors (TMGa, TEGa, TMAl, TMIn) as well as high purity NH_3. Donor and acceptor doping was done using SiH_4 and Cp_2Mg as precursors, respectively. Operating pressures of the system varied from 100–950 mbar and typical growth temperatures were $\sim 1000-1100°C$ for GaN and AlGaN compounds and 750–850°C for InGaN compounds.

2 Results and discussions

2.1 Evaluation of AlGaInP

To demonstrate the capabilities of the AIX 2600G3 reactor we loaded 7×2 inch wafer on one out of 5 satellites with a diameter of 6 inch to grow AlInGaP on GaAs substrates. Room temperature photoluminescence mapping was carried out and the obtained wavelength distribution across one $2''$ wafer is shown in Fig. 2. The obtained average wavelength is 592.41 nm with a standard deviation of 0.92 nm which is 0.16%. Basically little variation of composition is observed across the wafer except at the edges. 10 period AlGaInP/AlGaInP multiple quantum wells grown at 750°C with the optimized conditions
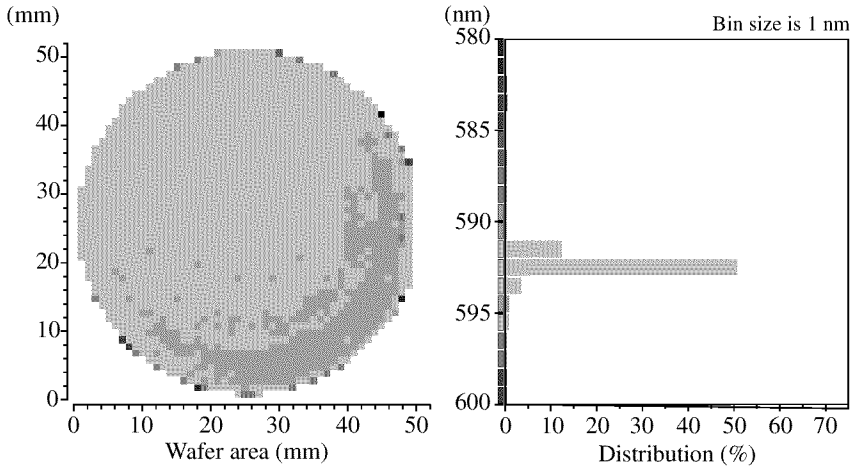
Fig. 2. Uniformity of wavelength of AlInGaP on 2″ GaAs. Average wavelength 590.78 nm, standard deviation 0.80 nm, 0.13%

show a PL-wavelength of 610 nm. The PL-wavelength standard deviation of one 2 inch wafer is less than 2 nm. The standard deviation of the PL-intensity is usually below 15% for one 2 inch wafer.

2.2 Properties of GaInP

The composition uniformity of GaInP has been demonstrated on 4″ GaAs substrates. The PL-wavelength distributions was obtained from automatically performed room temperature photoluminescence measurements. The average wavelength is 665.99 nm with a standard deviation of 1.68 nm which is 0.25%. As an example we demonstrate a good layer thickness homogeneity, represented by a standard deviation of only 0.24%. The average layer thickness of this specific layer is 4135 nm with a standard deviation of 9.8 nm. One can observe a rotational symmetry to the thickness distribution which corresponds to the reactor configuration including the very homogeneous temperature profile together with the well adapted rotation speed of the wafer. The rotational symmetry of the film thickness distribution represents a characteristic of the Planetary Reactor® with individual rotating substrates. The very low number of standard deviation in all important properties (layer thickness as shown, but also composition and PL-intensity) indicate the proper adjustment of the corresponding process parameters. These parameters are temperature and flow profile as well as rotation speed of main plate and wafers. Another important point to increase the device yield is the homogeneity of photoluminescence intensity. Again we will discuss a GaInP layer grown on 4″ GaAs substrates. The room temperature PL intensity distribution was measured. An average of 919 counts was obtained with a standard deviation of 112 counts (12%) which is an excellent value and would permit the use of nearly the whole wafer area to fabricate optoelectronic devices.

2.3 Growth of GaInAsP on 2″ InP

Since no 4″ InP wafers are currently available on a commercial base, GaInAsP was grown on 2″ InP. Since this material is very temperature sensitive, this is the ultimate homogeneity proof. The wavelength distribution of GaInAsP with an average wavelength of 1350.44 nm was measured. The standard deviation is 1.77 nm which is 0.25%. This result demonstrates
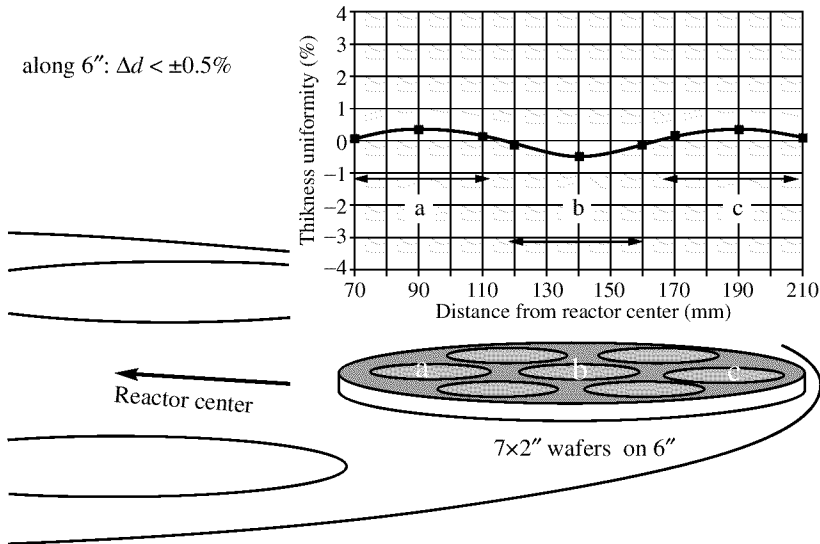
Fig. 3. AlGaAs/GaAs DBR thickness uniformity in the AIX 2600G3 reactor.

the very good uniformity obtainable in this kind of reactors.

2.4 Growth of AlGaAs and GaAs for electronic applications

Since the market for low power and high speed electronics based on GaAs is rapidly increasing we will demonstrate typical material systems in a large scale dimension. The growth of the corresponding layers is performed in the AIX 2600G3 9×4″ configuration. Here we will focus on typical layers used for the design of a AlGaAs based heterobipolar transistors (HBT). The resistivity distribution of a $Al_{0.3}Ga_{0.7}As{:}Si$ layer on 4″ GaAs wafer without edge exclusion was measured and evaluated. Hall measurements show an electron concentration of 3×10^{17} cm^{-3} and a mobility of 1600 cm^2/Vs. These data fit to the theoretically expected values for $Al_{0.3}Ga_{0.7}As$ to conclude that sufficient low oxygen and carbon levels are present in the sample. In accordance with the Hall data non destructive sheet resistivity measurements with a sheet resistance of 139 $\Omega/\square$ were measured. The standard deviation is only 1.4%. The thickness uniformity of this 2 μm thick 30% Al containing layer is below 0.25%. The rapid heating and cooling cycle of the G3 system allows to grow the p-type material at significant lower temperatures than the undoped and n-doped layers. The resistivity distribution of a GaAs:C layer grown below 550°C on a 4″ substrate was used to evaluate the doping uniformity. Using this doping technique we make use of the intrinsic carbon uptake from metalorganic precursors. The high hole concentration of 4×10^{19} cm^{-3} with a mobility of 99 cm^2/Vs and the sheet resistivity distribution with a standard deviation of only 0.9% proves the ability of this reactor concept to provide excellent doping uniformity in the temperature range lower than 800°C and down to lower than 550°C simultaneously without hardware change. These are the temperature intervals usually employed in HBT growth. These high uniformities in dopant distribution demonstrate the high potential for maximum yield in device fabrication. Unique thickness uniformity was shown as basic demand for the commercial production of electronic and optoelectronic devices like UHB LED, LASER, HBT and HEMT. To achieve the thickness uniformity the unique design of the reactor allows a linear depletion of Al, Ga and In in

the gas phase. We demonstrate the depletion of Gallium along the diameter of a 6 inch satellite. For these investigations we used AlAs/GaAs distributed bragg reflector (DBR) structures grown on wafers which were placed on rotating and intentionally non rotating satellites. Best thickness uniformity on DBR structures of ±0.5% were achieved for a low total carrier gas flow. A scetch of the reactor with the 35×2 inch wafer configuration on one 6 inch satellite together with the measured thickness distribution is shown in Fig. 3. With this total flow we observed a Ga efficiency for the DBR's of more than 40% in the 35×2 inch configuration and more than 50% in the 5×6 inch configuration.

2.5 Development of SQW- and MQW-InGaN/GaN structures for blue and green emitters

Further development of the above described reactor concept was made resulting in In-GaN/GaN SQW and MQW structures [5, 6]. Optimization of reactor process conditions has shown that V/III ratios less than 1000 can successfully be employed for the growth of GaN and AlGaN at up to 3 μm/hour without degradation of the electrical and optical properties. Typical background doping of GaN layer is $< 5 \times 10^{16}$ cm^{-3}. Thickness uniformity in the range of 1% have been achieved for both GaN and AlGaN films at deposition rates of larger than 2 μm/hour. Low temperature photoluminescence of GaN layers show strong excitonic emission with typical full width at half maximum (FWHM) of 3–4 meV at 4.2 K. For InGaN compounds, V/III ratios smaller than 3000 were employed for the growth of both single layer as well as quantum well and DH structures. In the present work, we investigated different interface treatments of MQW layers consisting of 10 stacks of 7 nm GaN and 5 nm InGaN to study the impact on PL wavelength and intensity. The InGaN-wells were grown under N$_2$ at 750°C and 200 mbar. The total flow was fixed at 16 slm. The GaN-barriers were grown under either N$_2$ or H$_2$ as carrier gas in the range of 750°C to 950°C at 200 mbar with total flow of 14 slm. PL wavelength and intensity were found to be strongly influenced by the introduction of growth interruptions and growth temperature discontinuities. Hence, we varied the barrier temperature while keeping the well growth temperature constant. The emission wavelength of the MQW's shifts with increasing growth temperature of the GaN-barriers to lower values, probably due to enhanced indium losses at higher temperatures. Simultaneously we observe a strong enhancement of emission intensity with increasing growth temperature of the GaN-barriers, due to lower emission wavelengths and an improvement of optical and structural quality of the barrier material. The HR-XRD spectra of the MQW's grown by using growth interruptions exhibit satellite peaks from the -4th to the +3rd order with sharp linewidths. The room temperature PL show single peak transitions without any yellow luminescence at about 470 nm with strong signal intensities depending on the growth conditions. The corresponding line widths (FWHM) ranges from 35 to 40 nm. The wafer to wafer as well as the run to run uniformity is in the range of about 2 nm standard deviation. The intensity distribution ranges around 10% standard deviation. Full wafer mappings of wavelength and intensity show a uniformity of about 2 nm standard deviation in wavelength (Fig. 4) and 20% in intensity for as grown material without any edge exclusion.

3   Conclusion

We presented comprehensive data concerning the growth of GaInAsP, GaInP, AlGaAs, AlGaInP and GaN based materials. Special focus was put on uniformity (typical data: 1% thickness uniformity and 1 nm wavelength uniformity for most of the materials) and electrical and optical characteristics of films grown in these machines. The data prove that AIXTRON Planetary Reactors® are the most flexible and efficient reactors to meet the
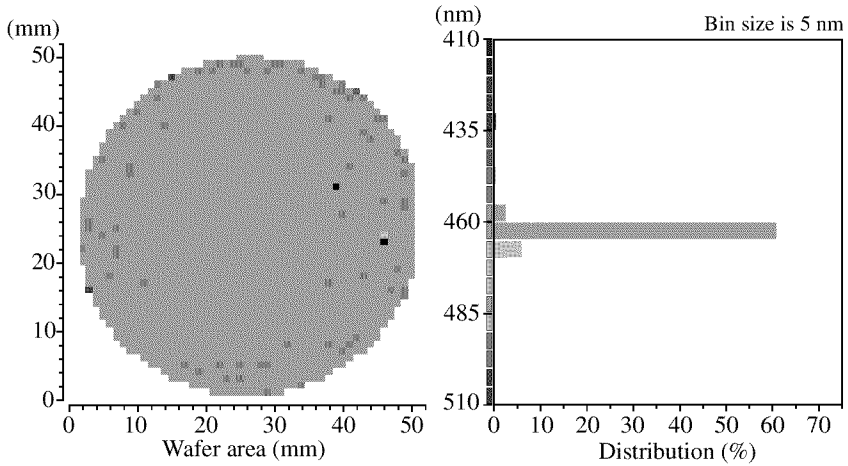
Fig. 4. Room temperature PL wavelength mapping of an InGaN/GaN MQW layer stack. Average wavelength 462.7 nm, standard deviation 1.9 nm.

demands of III–V manufacturing including sophisticated quantum wells and nanostructures for the next decade.

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